

THE HOLLOW CATHODE PHASE OF PSEUDOSPARK OPERATION

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Abstract

Reported here are results of a collaborative theoretical and experimental effort to develop useful predictive models of the hollow cathode processes that occur in the pseudospark and back-lighted thyratron. During pulsed operation there are several sequential modes of cathode behavior. High current (≈ 2 -100 kA) transport occurs during a highly emissive, or super-emissive mode of cathode operation (Phys. Rev. Lett. **60** (23), 2371 (1988)). Prior to this mode a hollow cathode mode occurs that is an essential step leading to the super-emissive mode. This hollow cathode discharge is also a source of an intense, high-brightness electron beam. In results presented here the electron beam is shown to be a consequence of the plasma cathode produced by hollow cathode ionizational processes, and the high electric field which is required to initiate high current conduction at the next phase of discharge is predicted from the simulation. Experimental results of a hydrogen hollow cathode discharge electron beam are also presented. An electron beam with pulse-length of 10's nsecs, peak beam current of 170 A, efficiency of 21% was measured at -20 kV applied voltage. The model is shown to be in good qualitative agreement with experiments. It is remarkable that these emission processes can be modeled at a microscopic level not possible for most technologically relevant cathodes. Based on a microscopic description of collisional, dissociative and ionizational processes, the model can predict transport and electron beam parameters including emittance and brightness.

Introduction

Pseudospark discharges occur in a hollow cathode geometry, conduct pulsed current with high di/dt ($> 10^{11}$ A/s) and produce an electron beam of very high brightness ($> 10^{10}$ A/m²rad²). [1-3] A closing switch with high di/dt is important to applications including lasers, accelerators, high power, and other short pulse applications such as kicker magnets in the storage rings, and high brightness electron beams are also important for a number of applications. We describe here a model and present experimental results describing the rapid plasma formation and the associated

development of virtual anode during the transient hollow cathode discharge (HCD). This HCD is key to the high di/dt , and the production of an intense electron beam.

In the sequential conduction phases of the pseudospark, two electron beam components have been observed. The first one is produced immediately following the breakdown event (which is usually triggered), and is typically a beam with energy comparable to the voltage switched, and peak current of ~ 10 -1000 A. The width of this component in time and its spread in energy depend on the evolution of the plasma produced in the discharge, or more precisely, the evolution of the potential distribution in the gap. This beam is produced during the HCD. Measurements of the properties of this component of the electron beam provide not only data needed for its eventual optimization in terms of current and brightness, but also provide a stringent test of the prediction of numerical model of pseudospark discharges. (The second component of the electron beam is related to the operation of super-emissive cathode mode that follows the HCD [4,5] (current ≈ 200 A, duration $\approx \mu$ secs, energy of several hundred eV) is not discussed here. [6])

The high current conduction [7-9] requires a high electric field on the surface of the cathode to initiate and support high-current electron emission. An understanding of the initial phase of operation, including the rapid transition of a virtual anode to the immediate proximity of the cathode, and the formation of a high-density, uniform plasma within the cathode-anode gap, are predicted in the simulation, and directly addresses the fast-rise, high-current conduction observed in the operation of pseudospark. The emphasis of work reported here is development of a predictive model for the plasma formation and the associated high energy, high brightness electron beams generated during the HCD phase. A description of the HCD electron beam in helium, and comparison with measurements in hydrogen are presented.

Theoretical Model and Simulation Results

A two dimensional, self-consistent model of the electrical properties of transient HCD which is used to describe the initial phases of a pseudospark discharge has been developed. The model consists of Poisson equation for the electrical field coupled to a fluid description of the electron and ion transport, with the important feature that the ionization source term in the electron and ion fluid equations is determined through a Monte Carlo simulation. The fluid equations determine the time and space dependence of the charged-particle densities. The space charge and self-consistent field from Poisson equation yield the particle

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currents. With the knowledge of electron current density distribution leaving the cathode and the electrical field distribution within the cathode-anode gap, the Monte Carlo simulation determines the ionization source term which, in turn, is input to the fluid equations. This model is referred as a hybrid fluid-particle model.[10]

An essential phenomena during the initiation of pseudospark discharge is the development of space charge. At this moment the plasma is collisional even though the electron mean free path can be on the order of the discharge dimension. The collisions between electrons and neutrals will dominate and the coulomb collisions between charged particles can be neglected. The energy distribution of electrons is therefore more energetic than that of ions. The result is a non-Maxwellian electron energy distribution. For this reason the model must be able to take into account the non-equilibrium charged particle transport and electric field distribution in a self-consistent manner.

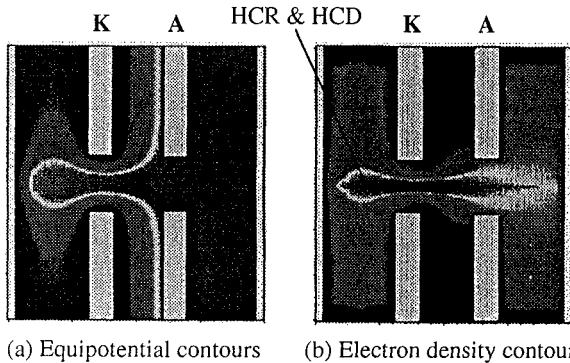
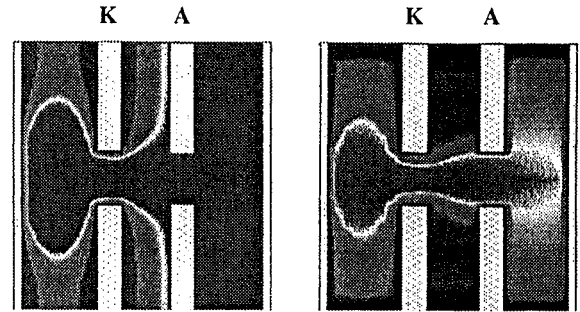


FIG. 1 Equipotential contours and electron density contours in 0.6 Torr helium gas with 2 kV applied voltage 50 nsec after the application of voltage.

Figure 1 shows the equipotential and electron density contours for operation at 0.6 Torr helium and a constant applied voltage of 2 kV. The contours were taken at 50.4 nsec after the application of voltage. In this particular calculation, the geometry is symmetrical (with a hollow cathode and a hollow anode). The electrode thickness and cathode-anode separation is 2.5 mm and 4.5 mm. Both electrode central holes are 5 mm in diameter. The HCR has a dimension of 3 cm in diameter and 0.7 cm in length. A trigger pulse is assumed to produce a uniform initial charged particle density in the HCR at the time when the voltage is applied ($t=0$). The electrical field at $t=0$ is almost uniform in the gap, with a small distortion in the region of the holes. As the initial electrons are pulled out of the cathode and towards the anode, they produce ionization in the gas. The secondary electrons are accelerated towards the anode, leaving behind a growing ion space charge field. If the trigger pulse is of sufficient amplitude, a plasma will form in the gap and distort the geometrical field. This will in turn increase the potential in the HCR as shown in Figure 1-a. The space charge distortion of the applied field just as the plasma begins to fill the HCR is such that the electron multiplication is a maximum at this point in time, and there is a rapid increase in the charged particle densities. The result is shown in Figure 1-b where a high electron density core (on the order of 10^{13} cm^{-3}) can be observed. During

this time a large displacement current spike has also been observed due to the increase in the field corresponding to this space charge.



(a) Equipotential contours (b) Electron density contours
FIG. 2 Equipotential contours and the electron density contours at 80 nsec after the application of high voltage. The collapse of anode voltage and the expansion of high-density plasma can be seen.

In general, with the application of a high enough voltage the plasma will begin to form first in between the cathode-anode gap or close to the cathode hole. The plasma expands from this point of formation towards the cathode. The potential which existed at the position where the plasma is first formed is pushed into the HCR as the plasma expands. Most of electrons created in the HCR oscillate between the high field sheaths until they lose most of their total energy in collisions. These low energy electrons are trapped in the low field region on axis behind the cathode hole through which they diffuse into the gap and then are accelerated in the remaining potential within the gap. These electrons comprise the observed electron beam. From simulation an electron beam with current density $\approx 20 \text{ A/cm}^2$ and peak energy of 700 eV was observed 30 nsec after the trigger with an applied voltage of 2 kV.

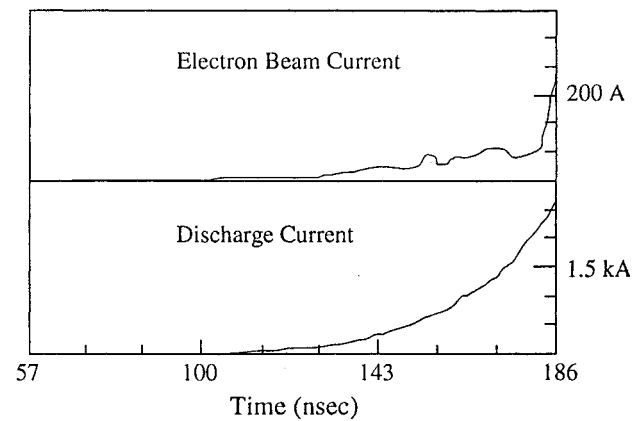


FIG. 3 Simulation results of electron beam current and discharge current with 0.5 Torr He at 10 kV voltage.

Figure 2 shows a snap shot of the equipotential contours and the electron density for the same discharge at 80 nsec after the application of high voltage. From Figure 2-a, the collapse of anode voltage onto the cathode surface can clearly be seen. This phenomenon is accompanied by the expansion of a high-density plasma core both within the HCR and in between gap as shown in Figure 2-b. With a 2 kV applied

voltage, the electric field on the cathode surface can be of the order of 10^7 V/m, producing a high electric field on the cathode surface.

Figure 3 shows the simulation results of both the discharge current and electron beam current. The discharge is in 0.5 Torr He at 10 kV constant applied voltage. Only the secondary emission from ions bombardment is included in the simulation and the ionization is assumed to be due to electron-impact. An electron beam with current of ≈ 200 A is predicted with a discharge current of 2.5 kA, which gives a beam to discharge current ratio of $\approx 8\%$. Another significant result is the high current rate of rise (di/dt on the order of 10^{11} A/sec at the end of simulation) was directly predicted from the simulation.

Experimental Results

In this section some experimental results related to the simulation work are presented. Figure 4 shows the experimental setup. The HCR was made of copper with a cylindrical structure, a cathode on one end and a quartz window on the other. The HCR has a dimension of 3.5 cm in diameter and 2.5 cm in length. The electrode central hole size and the thickness of insulators were both 3 mm. The discharge was initiated with a UV flash lamp at the back of cathode near the central hole through a quartz window. Cathode current was monitored through a $5\text{ m}\Omega$ current viewing resistor (CVR) and the cathode voltage through a Tektronix P 6015 high voltage probe. The electron beam was generated with an RC discharge circuit ($22\text{ }\Omega$, 16 nF). The electron beam current was measured with a fast Rogowski coil ($\leq 1\text{ nsec}$) at $\approx 1\text{ cm}$ behind the anode hole. A fast Faraday cup ($\leq 2\text{ nsec}$) is also available. Permanent magnets were used only for beam energy measurements.

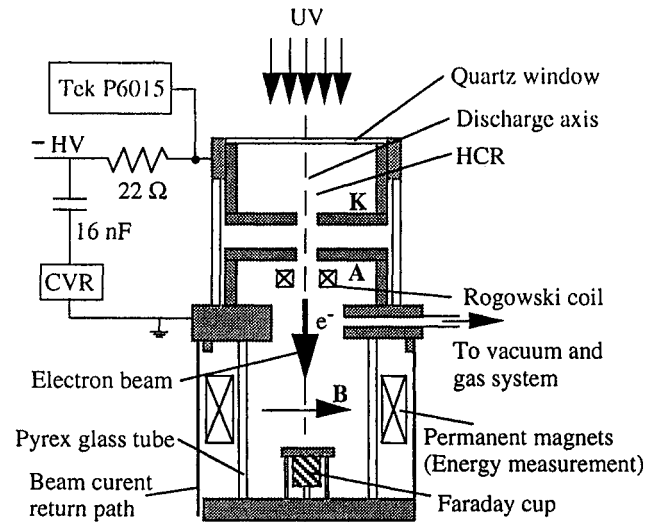


FIG. 4 The experimental setup for electron beam measurement.

The drift tube is a 41 mm Pyrex glass tube. Two copper screen cylinders were used to cover both sides of the glass tube. The inner copper screen was to provide the plasma electrons return path and was directly connected to the grounded anode. The outer screen provides the beam current

return path to the anode and can be detached from the anode when necessary.

Figure 5 shows the typical discharge current and the electron beam current at -20 kV applied voltage with 80 mTorr H_2 . The peak of the discharge current is ≈ 800 A and the electron beam ≈ 170 A, which gives a beam current to discharge current ratio of 21%. The pulse length is $\approx 50\text{ nsec}$. The pulse length is associated with the plasma formation processes within the cathode-anode gap and not easily controllable with external circuitry. The discharge current has a slower rise at the beginning of the pulse which corresponds to the build-up phase of the transient HCD. After this moment the discharge current increases over-exponentially as a result of fast increase of charge multiplication inside the HCR. The electron beam current has a similar behavior and the peak is coincided with the peak of discharge current.

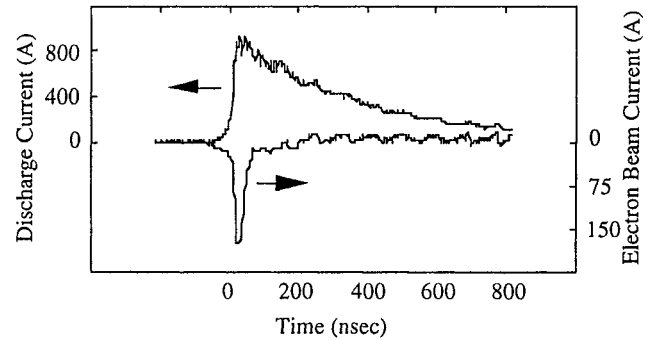


FIG. 5 The discharge current and the beam current at 1 cm behind the anode aperture.

Beam current dependence on gas pressure was also studied. A dramatic increase was observed when operated at lower gas pressure. The beam current increases by a factor of 4 with a pressure reduction of only $\approx 40\%$ (from 140 mTorr to 80 mTorr). The beam current was also found to increase with increasing applied voltages. The beam current increases from 10 A to 45 A when the voltage is varied from -14 kV to -20 kV in a 135 mTorr H_2 . These results suggest that when operated at a -40 kV voltage and 50 mTorr hydrogen, an electron beam with current of kA is feasible.

The electron beam energy was estimated with a high-pass filtering technique. The technique utilizes the $V \times B$ deflection that beam electrons experience when traversing a transverse magnetic field. Only those electrons with high enough energies can survive the deflection and still be collected by the Faraday cup. With different strength of the magnetic field different electron energy can be estimated. The spatial distribution of the magnetic field was measured and used as the prescribed field for a single electron trajectory computer simulation with electron energy as input parameter. With a capacitor discharge circuit at -10 kV (16 nF and $500\text{ }\Omega$) and 400 mTorr He, the peak beam current is $\approx 32\text{ A}$ at 2 cm behind anode. With increasing transverse magnetic the beam current is observed to decrease accordingly. The electron beam decreases both in beam current and pulse length. The latter portion of the beam current is observed to diminish first and the vanishing point represent electron beam with minimum energy set by the

magnetic field. Figure 6 shows the experimental results. The minimum beam energy is found to be $1.2 \text{ keV} \leq E_1 \leq 2.7 \text{ keV}$ for one pair of the permanent magnets and $4.2 \text{ keV} \leq E_2 \leq 7.7 \text{ keV}$ for two pairs of magnets. The source of error comes from the possible uncertainty of the precise position of Faraday cup in the transverse direction ($\approx \pm 1 \text{ mm}$). The upper curve of Figure 6 is the cathode voltage. On the same curve the minimum energy from trajectory simulation was plotted at the time where electron beam corresponding to different magnetic field vanished. The results indicate that the electron beam has energy close to and below the cathode voltage as predicted from the theoretic model.

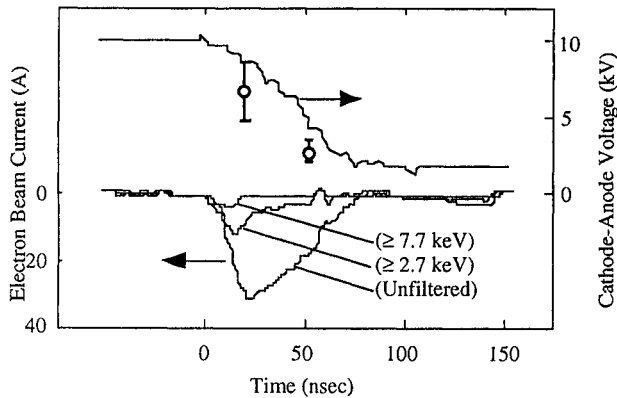


FIG. 6 Electron beam energy measurement with high-pass filtering method.

The propagation of this electron beam in an 80 mTorr H_2 was studied with radiachromic films at various locations behind anode. The method is time-integrated in nature and a beam divergence half angle $\approx 5.0^\circ$ is measured. Emittance can also be estimated with the assumption that the beam waist is at the anode position.[11] At 170 A and instantaneous energy of 10 keV a normalized emittance of 25 mm-mrad is found and a normalized brightness of $2.7 \times 10^{10} \text{ A/m}^2\text{rad}^2$ is calculated.

Conclusion

In conclusion a theoretical model for the initiation phase of the pseudospark discharge has been developed. The evolution of the discharge and the observed electron beam are found to be in good qualitative agreement with experimental observations. The high electric field which is required to

support a high current conduction at the next phase of discharge is predicted from the simulation. The model is important because the electron beam generated from HCD can be modeled with microscopic details which are usually difficult to incorporate for other technologically relevant cathodes, such as thermionic or metal cathode, for which surface physics are described only by phenomenological models using empirical data. In principle the model can be developed to predict beam parameters including emittance and brightness based on a microscopic description of collisional, dissociative and ionizational processes. Future work will include the theoretical study of beam emittance, dependence on circuits, applied voltage, gas pressure, and gas species.

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